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Designing cost-effective supply chains for plastics at the end-of-life

Baibhaw Kumar [a], Jean Pimentel [b], Natalia A. Cano-Londoño [c,f], Gerardo J. Ruiz-Mercado [d,e], Csaba T. Deak [a], Heriberto Cabezas [a,b,*]

[a] University of Miskolc, Miskolc-Egyetemváros, H-3515, Miskolc, Hungary
[b] Széchenyi István University, Egyetem tér 1, 9026, Győr, Hungary
[c] University of Twente, Enschede, The Netherlands
[d] U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH, USA
[e] Chemical Engineering Graduate Program, Universidad Del Atlántico, Puerto Colombia, 080007, Colombia
[f] Grupo de Investigación Fenómenos de Superficie-Michael Polanyi, Facultad de Minas, Universidad Nacional de Colombia Sede Medellín, Kra 80 No. 65–223, Medellín, Colombia

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ABSTRACT

Increased global plastic consumption and production boosted the amount of end-of-life (EoL) plastic. Also, 90 % of plastic EoL is either landfilled or incinerated. These unsustainable EoL pathways impact the environment and human health and waste valuable materials. Thus, improvements to the existing recycling infrastructure for sustainable plastic management are needed to enhance plastic circularity. Therefore, this contribution addresses optimizing cost-effective pathways for plastic recycling within the supply chain. The research uses mathematical optimization and the P-graph theoretical framework to calculate recycling costs, encompassing both capital expenditure and operational expenditure for various pathways of plastic recycling. The proposed methodology is applied through a detailed case study in Miskolc, Hungary, revealing estimated recycling costs ranging from 54.9 to 59.28 EUR/ton. This finding provides crucial insights into the economic implications of diverse recycling methods. Also, the study highlights the P-graph model's untapped potential as a resource for decision-makers in plastic recycling, particularly the enumeration of options for further consideration. The work's utility and novelty lie in the model's capability to design cost-effective pathways, offering a tangible contribution to the plastic recycling supply chain. Finally, this contribution offers economic solutions needed to ensure cost-effective sustainable plastic management solutions.

1. Introduction

The world is transitioning to a circular economy (CE) to promote more efficient and sustainable end-of-life (EoL) material management practices. A CE can be defined as an "*economic system designed with the intention that maximum use is extracted from resources and minimum waste is generated for disposal*" (Deutz, 2020; Londoño and Cabezas, 2021). The sustainable management of municipal solid waste (MSW) worldwide, particularly in developing nations (Godfrey, 2019), is challenging because of its complex, limited, and inefficient EoL supply chain pathways, which focus on landfilling, open burning, and open dumping, as shown by life cycle assessments (Laurent et al., 2014). EoL plastic is a pressing global concern due to its detrimental environmental, social, human health, and economic impacts. As an integral component of modern life, plastics permeated nearly every facet of society, offering undeniable utility and convenience. However, the widespread use and improper EoL management of plastics resulted in extensive pollution, ecosystem damage, and threats to public health.

Over the years, researchers have tried to find optimized pathways to curb this problem of EoL material mismanagement via network designs (Bertok and Bartos, 2018). A review suggested that most network designs are primarily based on four crucial aspects, i.e., mathematical models, supply chain management, operations research, and solid EoL material management (Van Engeland et al., 2020). After configuring all suitable pathways or network designs, the network's parameters must be set to optimize the supply chain according to a certain objective function. The objective function could be single or multiple, depending on the network and designer's requirements. Singular objective optimizations usually focus on either cost minimization or profit maximization.

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* Corresponding author. University of Miskolc, Miskolc, Hungary.
E-mail address: cabezas.y.fernandez.heriberto@ga.sze.hu (H. Cabezas).

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Abbreviations

CE	Circular Economy
EoL	end-of-life
MSW	municipal solid waste
CAPEX	capital expenditure
OPEX	operational expenditure
OECD	organization for economic cooperation and development
GRP	generic recycling path
COP	cost optimization path
MSG	maximal structure generation
ABB	accelerated branch and bound
SSG	solution structure generation
MIP	mixed integer programming
CP	collection points
KSH	Hungarian Statistical Office
TF	treatment facility
LCA	life cycle assessment

Conversely, multiple objective optimizations minimize criteria including travel distances between facilities (Chang and Wei, 1999), cost, environmental footprint, delinquency (Amin and Baki, 2017), or maximizing population coverage, responsiveness, etc. Various forms of EoL plastics are part of the supply chain loop. A closed-loop plastic supply chain is formed when a basic forward logistics (EoL stage) is connected with a reverse supply chain to reclaim that product from the start point (manufacturing stage).

Mathematical models aid in understanding the networks and have been used extensively by researchers to optimize supply chains (Bok et al., 2000; Dige and Diwekar, 2018). One such platform or approach is using the P-graph framework. The P-graph framework's fundamental algorithms rely on the structural properties built on process graphs to design and optimize activity networks (Friedler et al., 1992a,b). Proper structuring is one facet of network design frequently given insufficient consideration. Since supply chains are essentially complex networks, particularly in the case of large-scale applications such as energy distribution or EoL material management, it is common to find numerous structures, but optimal routes must aid in the efficient collection, transportation, and distribution of goods from different categories. The P-graph can generate a set of structures for even relatively simple processes or supply chains, as structure is an often-overlooked feature of process and supply chain design (Cabezas et al., 2018). A recent web-based tool, ADAM, has been developed for similar optimizations in case of limited mathematical insights. ADAM makes modelling easier by implementing simple and intuitive graph-based frameworks that let users define dependencies between objects, people, and locations (Hu et al., 2022).

The modelling tools aid in producing the economically feasible and best profit-making pathways for the MSW supply chain. The overall network for MSW management in cities has evolved over the years. However, much must be done to optimize the costs of material collection, sorting, recycling, and disposal. Emphasis needs to be stressed on plastic since recycling plastics in the form of granulates or crumbs for remanufacturing is common and cost-effective in many locations. According to Chang and Wei (Chang and Wei, 2000), to accomplish the best collecting route and ideal recycling network architecture, it will be necessary to build mechanical sorting plants to finish the recycling cycle. Correct container sizing, personnel reduction, on-route compaction, and placement of transfer stations in the integrated MSW management system are some elements influencing the process. It is often observed that certain objective functions, such as environmental, social, and economic efficiency, often conflict with various models solved simultaneously (Saif et al., 2022).

To provide a comprehensive overview of significant studies in plastic recycling, both experimental and modelling, and to identify research gaps that our current study addresses, a few recent studies have been compiled in Table 1.

These models can be enhanced by adding a more comprehensive economic assessment. By addressing this gap, our study contributes to the advancement of plastic recycling research, providing a robust and economically optimized model for decision-makers and stakeholders in the field. This research contribution delves into the EoL plastic recycling pathway, focusing on its economic feasibility and optimization within an urban city level context. For this, a systematic methodology is developed to find alternative pathways that improve the supply chains of EoL materials. This method is based on the P-graph-theoretic framework, which permits the generation of the n-best recycling pathways by calculating recycling costs, encompassing both capital expenditure (CAPEX) and operational expenditure (OPEX). A comprehensive case study conducted for Miskolc, Hungary, serves as a practical exemplar, shedding light on the viability of realistic plastic recycling in a specific urban landscape.

Furthermore, it highlights the potential utility of the P-graph framework as a decision-making resource for stakeholders vested in plastic EoL management scenarios. Analysing the various recycling pathways generated provides the stakeholders with insightful information concerning the alternatives of the EoL material from a CE perspective. Thus, the findings presented herein are relevant to policymakers, businesses, and researchers. They offer a pragmatic pathway toward promoting environmentally responsible EoL management while ensuring the financial sustainability of plastic recycling endeavours. In section 3, we discuss the methodology adopted in our investigation, and below is the research question to be addressed in this study.

- How can cost-effective pathways for recycling EoL plastics be designed using the P-graph framework?

The research highlighted a gap in understanding the underexplored role of the P-graph framework in cost-optimized pathways for sustainable EoL materials management. Additionally, we contribute by

Table 1
Recent studies and modelling approaches in plastic recycling pathways covering the representation of recently developed models.

Modelling approach	Remarks	Reference
Mixed-Integer Programming (MIP)	Introduced three MIP models to address network design problems for mixed plastic waste (MPW) supply chains.	Wang and Maravelias (2024)
Superstructure Optimization	Developed a systematic framework cantered on superstructure optimization to identify the most efficient economic and environmentally friendly approach for managing plastic waste.	Hernández et al. (2024)
Mixed-Integer Nonlinear Programming (MINLP)	Developed a novel multi objective optimization model based on MINLP to optimize plastic waste sorting and recycling processes.	Lee et al. (2022)
Network Flow Model	Formulated an optimization problem from the perspective of reducing global ocean plastic pollution and created a novel framework based on a network flow model.	Li et al. (2022)
Linear Programming (LP) and Mixed-Integer Linear Programming (MILP)	Developed LP and MILP models for matching sources of waste plastic with recycling facilities to optimize recycling networks.	Aviso et al. (2023)

investigating the application of the "P-graph" through a case study, offering practical insights for designing efficient and sustainable recycling strategies.

2. Global contrivances in the recycling of plastics

Plastics are one of the fastest-growing EoL streams in the world, and their manufacturing accounts for 6 % of the world's oil use (Gündoğdu and Walker, 2021). The material's circularity, carbon impact reduction, and social awareness are all essential components of a successful business strategy that can close the circle of the plastic industry. Recyclers and plastic processors might benefit from institutionalization and organization if end-user industries provide feedback on the market and quality demands for recycled plastics. For instance, in India, developing socio-technical models, bringing the EoL management informal sector into the formal economy, setting up facilities for material recovery, developing support structures and institutional frameworks, and putting in place a technology-supported knowledge management system are the primary resource recovery challenges from EoL plastic. Fig. 1 shows the MSW landfill (percentage) and recycling rate (percentage) allocation of municipal solid waste by treatment operation for some countries whose data were available. It is observed that the Scandinavian and Nordic countries, including Germany, Slovenia, and South Korea, have low landfills and high recycling rates. In contrast, countries such as Hungary and Poland have recycling rates between 20 and 30 %, yet landfills contribute 40–50 %, which is contrary.

To understand the reasons behind the low recycling rates and the challenges in the supply chain, we compiled a summary of identified challenges and proposed solutions available in the literature, shown in Table S1 (see supplementary material). The takeaway lessons from the mentioned case studies could help researchers identify some of the critical reasons for the low recyclability of plastics, along with other issues at various recycling levels.

3. Methodology

Plastics are technically sophisticated, inexpensive, and suitable for various uses. The crucial sustainable materials management issue with plastic is how plastic products are handled at the end of their lifecycle. Several countries have adopted distinct policies to manage this problem (Knoblauch and Mederake, 2021). Collecting EoL plastics, processing, manufacturing, and selling recycled products is complex because of their chemical additive variability, cost feasibility, and logistics material inefficiencies (Chea et al., 2023). Henceforth, cost-optimizing the supply chain can aid stakeholders involved in plastic EoL management to design more sustainable EoL pathways and technologies.

The methodology proposed in this work starts by defining the synthesis problem to be solved. This involves specifying the relevant components, i.e., activities, facilities, or locations, that can be part of the recycling pathway. Fig. 2 depicts a generic recycling path (GRP) on its left-hand side and the cost optimization path (COP) next to it. The GRP is a broader pathway that shows the various stages of the supply chain for managing plastics at the EoL. In our study, the COP pathways are divided into five groups of activities for whose plausible components must be determined: collection, transfer, transport to MSW facility, MSW facility, and sale. Fig. 2 depicts a stepwise methodology of the present study framework on its right-hand side. The components of the collection activities are the elements of the sets of sources and collection points. On the one hand, the sources, or generators, are the origin of the EoL material to be recycled (e.g., schools or industries in Fig. 2) and must be specified considering the region's characteristics and the largest plastic generators. For modelling, generators can be grouped by economic activity, and their location and expected plastic generation must be specified. On the other hand, the collection points are the existing or proposed locations where the EoL plastic from distinct sources must be gathered before being sent to the treatment. Identifying these points also involves specifying their region location and maximum capacity. The greyed-out options represent EoL material management alternatives that exist in broader MSW management systems but are excluded in this study to maintain focus on the cost-optimized plastic recycling pathways. This diagram illustrates a simplified pathway for clarity and illustrative purposes, rather than an exhaustive representation of all possible recycling and disposal methods.

The MSW facility activities comprise a set of plausible treatment plants for the problem. Specifying these plants for the problem involves identifying the available facilities in the region (or those proposed by the designers) and their location. In addition, the recycling methods available in each facility, as well as their cost functions, need to be specified.

The transfer and transport components are specified by considering the location of sources, collection points, and facilities. These transport operations connect each source with each proposed collection point and each collection point to the distinct facilities. The sales activities entail the final distribution of the recycled material, which can involve transport to final clients or simply the in-house selling of the product. The logistics and transportation costs can be associated with the operations in these activity groups if they must be evaluated. Once these components are specified, the graph theoretic approach based on P-graphs, known as the P-graph framework, represents the system's plausible components and identifies the n-best recycling pathways for the EoL materials according to the total cost.

3.1. Overview of the P-graph framework and previous work

Problems involving the design or synthesis of process networks can be handled efficiently using the P-graph framework. It offers an advantage over numerical methods for process network optimization

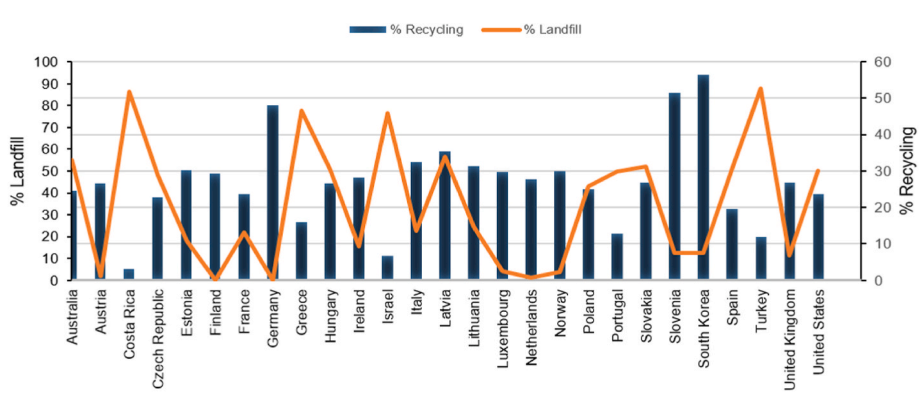

Fig. 1. Graphical representation of countries with their respective municipal solid waste recycling rate (%) and landfill rate (%) (Data source- (Municipal waste, 2017)).

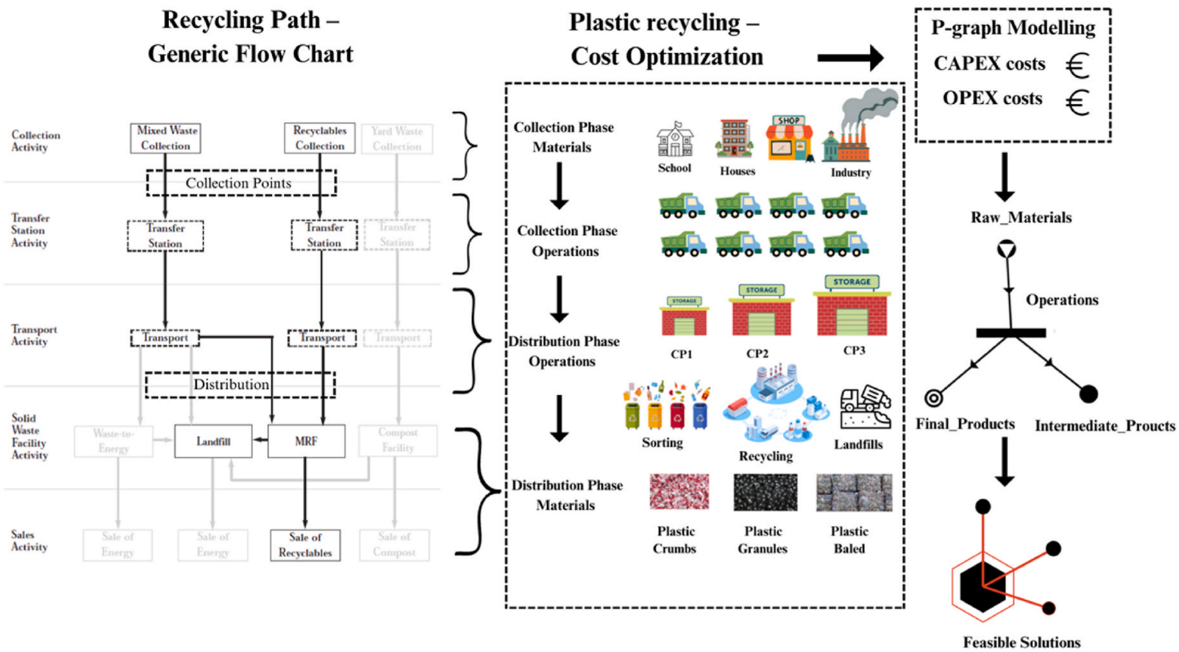

Fig. 2. Methodology for generation of alternative recycling pathways of end-of-life plastics (Recreated from (US EPA, 1997)).

when combined with the rigorous mathematical toolset of the axioms and theorems (Friedler et al., 1992a,b). It consists of two types of vertices/nodes. M-type nodes are "materials" depicted by circles, and O-type nodes are horizontal bars depicting "operations," as shown in Fig. 3 (a). These nodes are connected by directional arcs showcasing the directional flows of elements such as material, energy, emergy, money, services, etc. The two node types in the model cannot be adjacent. Thus, when combined, these sets form the feasible solutions as graph structures. Another linchpin to modelling a P-graph is the axioms that govern the graphical model's construction and should be carefully applied while defining the problem (Cabezas et al., 2018).

The networks fulfilling these axioms are logical recycling pathways from the structural point of view. Hence, they are termed *solution structures* (Friedler et al., 1995a). The algorithms of the P-graph framework exploit the structural properties of the problem's initial structure to facilitate the optimization procedure. These algorithms, listed in Fig. 3 (b), are (i) maximal structure generation (MSG), (ii) solution structure generation (SSG), and (iii) accelerated branch and bound (ABB). Algorithm MSG creates the maximal structure of the synthesis problem; this structure represents the union of all solution structures of the problem, i.e., solutions that fulfil the framework's axioms (Friedler et al., 1993). The SSG algorithm enumerates all these solution structures, thus identifying feasible recycling pathways from a structural point of view (Friedler et al., 1995b), and has been demonstrated to reduce the problem search space up to 99.99 % from an initial size of more than 34 billion solutions to 3465 solutions (Friedler et al., 1992a, b). Algorithm ABB solves the associated mixed-integer problem of the process-synthesis problem and determines the optimal structure. It can also identify the second, third, or any of the n-best structures, providing a ranked list of alternative solutions to the problem. Therefore, the output of the ABB is termed as the set of n-best solutions of the problem, as it comprises not only the optimal but also the ranked list of alternative structures that solve the problem (Friedler et al., 2022). Here, the mixed-integer problem comes from the interaction of binary variables, which represent the inclusion or exclusion of operating units in the recycling pathways, with continuous variables, such as material cost and

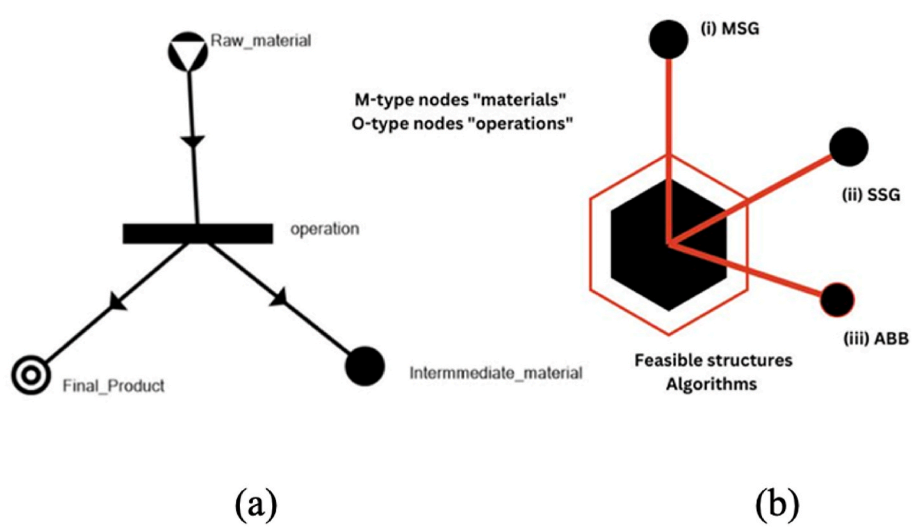

Fig. 3. (a) Basic components and (b) combinatorial algorithms in the P-graph framework.

flow.

The P-graph framework has been extensively used in various supply chain models (How et al., 2016) with mixed integer programming (MIP) (Lam, 2013) problems such as regional development assessment (Lam et al., 2010), energy saving, and pollution reduction process integration. It also addresses the uncertainty/reliability in raw materials for renewable energy products with reliability of availability (Klemeš & Varbanov, 2015). The supply chains and logistical networks must be structured from an integrated perspective, addressing different goals, to function in the modern industrial and market context, which is characterized by volatility and unpredictability (Bortolini et al., 2022). The P-graph models can also be extended or hybridized with other computational software such as WEKA or MATLAB. Ali et al. (2022) proposed a hybrid framework based on P-graph and WEKA to develop a decision-making tool for EoL material management strategies (Ali et al., 2022). The P-graph has proven its efficacy in EoL material management, particularly within the CE framework (Fan et al., 2020). Previous applications include developing integrated EoL material management systems and synthesizing waste-to-energy processing networks, showcasing its capability to handle problems with high combinatorial complexity (Ong et al., 2017).

Notably, P-graph's algorithmic process synthesis abilities have been harnessed for waste treatment and long-term technology planning, extending its utility to multiple periods. Furthermore, the tool is applicable in synthesizing resource conservation networks, specifically in the context of direct reuse/recycle schemes (Lim et al., 2017). Collectively, these studies underscore the versatility and effectiveness of the P-graph in tackling diverse challenges within EoL material management.

However, limited attention has been given to models in the context of EoL plastic management. An integrated P-graph-life cycle optimization framework proposed recently by Phuang et al. (2023) aims to optimize EoL plastic management pathways by balancing environmental and economic concerns through P-graph combined with life cycle assessment and costing.

3.2. General formulation for end-of-life pathway synthesis

The proposed formulation represents the components comprising the EoL pathways (recycling, landfilling, incineration, energy recovery) as part of the initial problem's superstructure. This superstructure must constitute a representation of a generic plastic EoL management problem. Thus, the components of the synthesis problem described before (Fig. 2) (i.e., sources, collection points, facilities, products, and transport units) are represented as P-graphs. Fig. 4 shows this structure for a general case with N sources, C collection points, K facilities, and J products per facility. The first group of transport operations, i.e., the transfer activity group, has a total of $N \times C$ horizontal bars that relate the distinct sources to the collection points. Similarly, the transport activities have $C \times K$ nodes connecting the plausible collection points to the evaluated facilities.

The operations in each facility are case-specific, as they depend on the units available or proposed by the designers. Thus, the plausible recycling processes inside the facilities are not generalized and must be individually specified in the structure. Moreover, not all facilities may generate the J products. Therefore, the connectivity between products and facilities also can vary for each case. The structure presented in Fig. 4 is a generic representation of the decisions to make in recycling problems. It can be deployed to represent assorted scenarios in

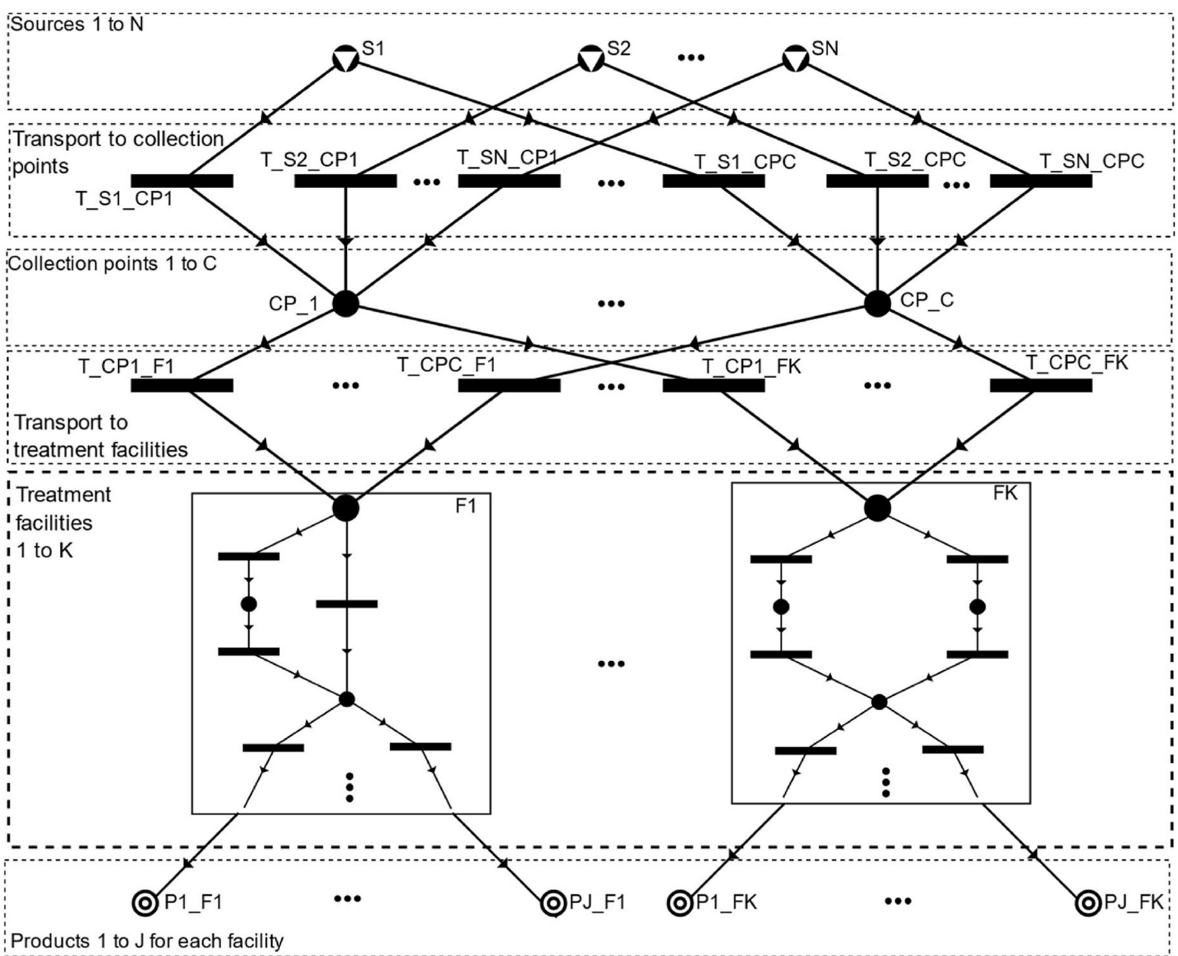

Fig. 4. The general P-graph structure for synthesizing pathways for recycling end-of-life plastics.

formulating synthesis and analysis problems.

Two primary parameters must be associated with M and O-type nodes, as well as the arcs connecting them. Which are.

- M-type nodes must be associated with maximum and minimum quantities and the associated costs of materials, i.e., upper and lower bounds and material price.
- O-type nodes must be associated with annual investment and operational expenses and parameters for cost estimation. For illustration purposes, in this work, the costs are estimated as linear functions of the unit's scaling factor, i.e., the unit capacity. Consequently, the parameters of fixed and proportional costs must be specified for each O-type node. Moreover, a limit can be set on the minimum and maximum operation capacity and payback period.

The arcs are associated with the flow rates of material and energy produced or consumed by the units. Because of the model used for illustration in this work, their values are related to the flows occurring when the unit's capacity equals one.

Fig. 4 provides the general structure of recycling pathways for EoL plastics. In this structure-

- *Sources* (S1 to SN) represent various starting points for generating EoL plastics.
- *Transport to Collection Points* (T_S1_CP1, T_S2_CP1, etc.): These denote the transportation links from the sources to the collection points.
- *Collection Points* (CP1 to CP_C): These are intermediate stations where plastics are gathered before being transported to treatment facilities.
- *Transport to Treatment Facilities*: These represent the transportation of collected plastics from the collection points to the treatment facilities.
- *Treatment Facilities* (F1 to FK): Each facility is designed to process, recycle, or dispose of specific types of EoL plastic.
- *Products* (P_J_F_1, P_J_FK) represent the recycled products emerging from each treatment facility.

The arrows indicate the flow of materials from sources, through collection points, and eventually to treatment facilities. This general structure illustrates the recycling pathways in the P-graph model. Furthermore, this structure will serve as the foundation for our modelling in the P-graph software, allowing us to minimize costs or maximize the utility of recycled products. Therefore, this diagram visually represents the process and forms the basis for our computational modelling.

As previously mentioned, the parameters of operating units and materials and their attributes can be associated with their corresponding nodes in the model. Herein, a simple model based on unit scaling factors is employed for illustration purposes. However, more complex relationships of cost and production can be employed if required.

4. Plastic at the end-of-life case study

4.1. Description of the case study

In 2020, almost 370 million tons of plastic were produced globally, including 58 million tons produced in Europe (Plastic Europe, 2020). Production will not decline anytime soon. This huge volume of plastics creates an extra burden on EoL management facilities. The European Union (EU) considers this in its regulations and calls for a recycling rate of 50 % for plastic packaging in 2025 and 55 % in 2030 (European Commission, 2018). In Hungary, 1605 companies produced plastic items in 2020, with a drop from the previous year. Notably, the number of businesses in this sector has steadily declined over the past few years (STATISTICA, 2023). Plastic contributes approximately 35 % of the MSW in Europe. However, in Hungary, there are limited operating transfer and sorting plants (6000 public collection facilities) for an optimal recycling framework, as shown in Fig. 5.

Eke and Havasi (Eke and Havasi, 2021) described Hungary's MSW collection and planning issues. The study suggests that the efficacy of the MSW collection system must be improved by enhancing the efficiency of the municipal waste collection system. This improvement depends on considering numerous parameters and building a comprehensive national database. The database should quantify the factors influencing transportation planning and could be developed in cooperation with current system operators. The study emphasizes the importance of this database for justifying new ideas and ensuring their reliability. In-depth research was done in the US (Rudolph et al., 2017) to comprehend the costs and effects of plastics and their recycling. The required information on the collection is challenging to obtain, and a lot of work, such as installing proper data collection systems and monitoring, must be done on the collection, sorting, and processing to support efficient handling at EoL. Henceforth, this study aims to identify the logistics gap and data needs in the plastic EoL supply chain by employing the P-graph framework to determine the best cost-based EoL networks. The city of Miskolc in "Borsod" County in Hungary was selected as a realistic case study to demonstrate the findings of the proposed approach. Miskolc City covers an area of 236.7 km^2 with a population of 157,639 as of 2016. The amount of MSW in kg/person collected from households per inhabitant of various regions of Hungary is between 385 and 387 kg/person (Hungarian Central Statistical Office, 2021). The selection of this particular city is due to the availability of data from the operational plastic recycling facility in Miskolc. For this case study, the amount of plastic to be treated is estimated to be in the city, equivalent to 30.5 kg/person/year, assuming a recycling rate of 40 % (Bíró-Nagy et al., 2023). Hence, the case study considers approximately 11,782 tons per year for recycling plastics in the city. Besides, a maximum of 10,000 t/year is set as a market constraint for the upper bound for the products, and it is assumed that moderate material is lost in the operations; according to previous contributions (Chea et al., 2023), close to 2 % of the material can be loss during the process. Thus, a conservative 1 % material loss in each unit is assumed here. The analysis is performed by looking for recycling paths of the lowest total cost, i.e., the optimization objective is to minimize the total cost of the alternatives.

4.2. Explanation of the cost calculation methodology

4.2.1. Collection phase – materials and operations

The first step in our research methodology is to specify sources for EoL materials where the collection is carried out. Naturally, the determination of sources largely depends on the nature of the EoL material being analysed, the specific final users, and the conditions of use. In this case study, the sources pertain to specific points in the city used for plastic collection. The collection process is critical as it is the foundation for subsequent supply chain calculations. The collection places within the city of Miskolc are defined by retrieving data from the existing recycling facility in the city and are primarily classified into four distinct categories.

- *Schools:* Used plastics are collected from educational institutions such as schools. These locations serve as one of the primary sources of recyclable plastics.
- *Industries:* Industrial establishments are another crucial category for plastic collection. Industries often generate significant amounts of EoL plastic, making them a vital component of the recycling supply chain.
- *Shops:* Retail shops and commercial establishments also contribute to EoL plastic generation. This category encompasses various types of businesses.
- *Households:* Residential areas, including households, are integral to EoL plastic collection. Household MSW forms a substantial portion of the recyclable plastic collected.

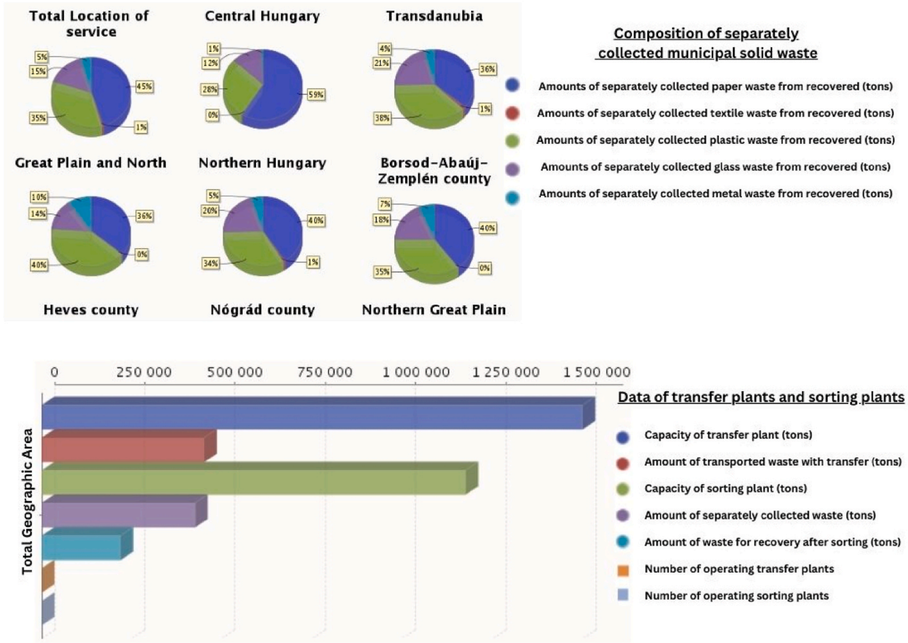

Fig. 5. Status of sectoral and regional distribution of separated municipal solid waste collection and several transfer and sorting plants in Hungary (Based on data from (Hungarian Central Statistical Office, 2021)).

Consequently, each category is regarded as a source in the model. We estimate the annual generation of EoL plastics within the city to initiate the analysis. This estimation is performed in light of the statistics of plastic EoL generation per capita reported by KSH (Hungarian Central Statistical Office, 2021) and the city's population; thus, it is assumed that approximately 11,782 tons of EoL plastics are generated yearly. The city's specific characteristics influence EoL plastics distribution among these categories. They may vary in other locations; herein, this was estimated based on specific information provided by the recycling plant. A single treatment facility, which represents the plant available in Miskolc, was defined in the case study. Here, we have determined that the operations available for treatment comprise two types of sorting (manual or automatic) and three types of mechanical recycling, i.e., baling, shredding, and pelletizing. The last three units can generate the three types of plausible products; moreover, an alternative to recycling the material is transporting it to a landfill. The maximum flow of material that can be landfilled is 4712 t/y.

The total annualized cost of the units is partitioned into CAPEX and OPEX, which are estimated via fixed-charged linear cost functions in this work. Thus, the CAPEX and OPEX for each operation are estimated via fixed and proportional parameters, i.e., for the operating unit i, they can be computed as

$$CAPEX_i = \frac{Cap_{Prop}}{PP} x_i + \frac{Cap_{Fix}}{PP} \tag{1}$$

$$OPEX_i = Op_{Prop} x_i + Op_{Fix} \tag{2}$$

where Cap_{prop} and Cap_{Fix} are the proportional and fixed part of the CAPEX, respectively; similarly, Op_{prop} and Op_{Fix} denote the proportional and fixed part of the OPEX; PP is the payout period utilized for annualization (assumed here as 10 years) and x_i is the capacity (scaling factor) of the operation i. Naturally, depending on the unit's nature, one or more of the parameters in Eqs. (1) and (2) may be regarded as zero.

- Fixed costs, i.e. p_{Fix}: These do not change with throughput and represent the base investment and operational expenses needed to keep the facility functional. And, Op_{Fix} the fixed (constant) part of OPEX, which accounts for baseline operational costs that do not change with production volume (e.g., minimum staffing costs).
- Proportional costs Cap_{Prop} and Op_{Prop}: These scale with the amount of plastic processed, covering consumables, energy, and additional labour costs.
- The payout period PP is used to annualize the fixed CAPEX costs over time.

Concerning the cost of transport operations, their annualized CAPEX is estimated at constant value of 3000 EUR/y, as transport operations are assumed to be dominated by the operating cost. Accordingly, the fixed portion of OPEX is estimated as the labour costs, which are computed assuming the wage of two operators and an annual salary of 10,416 EUR. On the other hand, a factor of 0.174 EUR/km t is assumed to calculate the proportional fraction of the OPEX (in EUR/t of transported plastic) by considering the distances of a round trip between the two connected locations.

In the case study, we have identified four collection points (CP) where EoL plastics are initially gathered. Thus, transportation costs between CP and sources depend on the distances between these CPs and the categorized collection places. The matrix of transportation costs for these locations is shown in the supplementary material in Table S2. Similarly, Table S3 shows the distance and operating cost for the transportation unit between the CP and the treatment facility (TF). It is important to note that the number of CPs and TFs may differ in other cases due to variations in city conditions.

4.2.2. Description of units in the treatment facility– materials and operations

In this case study we delve into the crucial aspects of sorting and recycling collected plastics, ultimately determining whether they are transformed into valuable recycled products or end up in landfills via the operating units defined in the TF. The effectiveness in defining the TF's units is pivotal in aiding the sustainable management of EoL plastic. It is important to emphasize that the costs incurred at different stages of the plastic recycling supply chain, including CAPEX and OPEX, are highly contingent upon various local conditions and factors. These conditions can vary significantly from one geographical area to another, reflecting each region's unique economic, environmental, and infrastructural circumstances. Table S4 in the supplementary material 1) provides a comprehensive breakdown of the CAPEX and OPEX components involved in our recycling cost model. These expenditures encompass the initial investments and considerations (Larrain et al., 2020) required to establish and maintain essential infrastructure in the recycling facilities (Sinnott and Towler, 2020).

Within the assumed model, users are afforded the flexibility to input a price parameter for the operation of the machine equipment in the form of the parameters in equations (1) and (2). The rationale behind incorporating these parameters lies in the inherent variability of machine equipment and energy prices across different geographical locations. This user-specified input enables the generation of novel pathways through the P-graph model, fostering adaptability to diverse contexts. The remainder of the section estimates these parameters for the distinct units in the TF. On the one hand, the CAPEX is represented by the investment costs of each unit, which are estimated based on reported units' prices. For this case study, it was assumed that the effect of the unit size on the annualized investment cost is negligible; consequently, Cap_{Prop} is assumed to be zero. Nonetheless, this parameter is introduced as it may be relevant for other problem instances. On the other hand, the units' OPEX parameters were estimated by considering labour costs for the fixed fraction and the unit energy expenses for their proportional fraction. Determining the proportional OPEX fraction involves a straightforward calculation wherein the kWh capacity of the machine required to process one ton of plastic is multiplied by the prevailing energy price of the respective region or country. These parameters are estimated via reported energy consumption and processing capacities retrieved from literature and vendors. As an illustrative example, the industrial energy cost in Hungary stands at 0.30 EUR/kWh, a figure employed in the computation of the proportional costs outlined in the pricing tables. This approach ensures that the model reflects the regional nuances of energy pricing, enhancing its applicability and relevance across varying geographical settings. The final CAPEX and OPEX parameters, as detailed in Tables S3–S7 in the supplementary material, are crucial inputs for the P-graph model. This model is a comprehensive analytical tool, integrating the cost data and other relevant parameters to evaluate the overall expenses incurred in plastic recycling. By incorporating the localized CAPEX and OPEX parameters, we gain insights into the financial implications of recycling plastics in Miskolc, Hungary.

Overall, the units in the TF are pivotal in determining the fate of collected plastics and optimizing the use of resources. The variability in costs underscores the importance of tailoring recycling strategies to the unique conditions of each locality. This research accounts for these variations, ultimately contributing to a more nuanced and context-aware approach to managing plastic at EoL in Hungary and, potentially, other regions of the world with different conditions.

5. Results

This section presents the case study model's outcomes, highlighting the application of the proposed approach in optimizing the plastic recycling supply chain based on input parameters, cost considerations, and network synthesis. For the present model, we employed the ABB algorithm to find the n-best alternative recycling routes in terms of total cost by employing the software P-Graph Studio (P-graph community, 2020). For this, the software draws the initial problem structure, and the parameters of operating units and materials described in the previous sections are associated with their corresponding node. The parameters for CAPEX and OPEX described in the supplementary material, Cap_{Fix}, Cap_{prop} , Op_{prop}, and Op_{Fix} can be directly introduced as the fixed and proportional pieces of the investment cost, and the fix and proportional components of the operating cost in the software P-Graph Studio. Based on this input, algorithm ABB systematically explores different network configurations, generating alternative solutions. In this instance, the 100 best alternative pathways were generated within the P-Graph Studio; however, the number of solutions can be iterated based on the model.

At the outset, the MSG algorithm is implemented to eliminate structural infeasibilities. In this case, the initial structure is equivalent to the maximal structure, as no structural infeasibilities were introduced. Fig. 6 illustrates the maximal structure generated by the P-Graph Studio, showcasing the complexity and interconnectivity of potential EoL supply chain pathways. This representation offers valuable insights into the diverse range of configurations that can be considered. It is worth noting that an additional unit (obligatory pickup) is a structural constraint that takes the information on the existence of all sources and ensures their plastic flows to be treated. In the whole supply chain, different sources (e.g., households, schools, industries, and retail centres) generate varying amounts and qualities of EoL plastic. If the model were to allow selective inclusion of EoL material sources, it could result in partial recycling solutions that ignore certain EoL streams, leading to unrealistic cost estimations and inefficiencies in EoL material management planning. The "obligatory pickup" function ensures that every source of EoL plastic is included in the solution.

Fig. 7 (a) and 7(b) depict selected cost-effective pathways derived from the P-graph model. These pathways highlight the optimization of the EoL supply chain with a keen focus on minimizing costs while maintaining material efficiency.

The user can check the pathways and the transportation routes similarly for all the structures generated by the P-graph and to choose the best cost-friendly pathways.

Fig. 8 depicts the final recycling costs associated with 100 solutions generated by the P-graph model and allows for a clear comparison of cost variations among the alternative pathways. Each pathway differs in transportation complexity and operational requirements. Some solutions favor shorter transport distances, reducing fuel and labour costs, and increasing operational expenses. Pathways prioritize transportation to a centralized recycling facility, minimizing sorting costs but increasing logistics expenses due to longer transport routes. Lower-cost solutions often involve simpler logistics but higher operational intensity (e.g., more sorting at collection points), while higher-cost solutions may include more direct transport routes with reduced sorting efforts. Decision-makers can use these insights to select a recycling strategy that balances cost efficiency with practical feasibility, depending on local infrastructure and policy priorities (for example, geographical constraints of the area, failure possibilities in the collection points, etc.). By analysing these 100 pathways, as shown in Table S8 (supplementary material), stakeholders can identify the most economically feasible and logistically viable plastic recycling strategies, making informed decisions to improve EoL material management efficiency.

The y-axis represents the estimated recycling cost for one ton of plastic (EUR/ton), ranging from 54.9 to 59.28 EUR/ton of plastic collected. The x-axis enumerates the solutions. Initially, there was a noticeable increase in cost from solution 1 to around solution 20, where it stabilized at nearly 59 EUR/ton for a significant portion of the solutions. Towards the end of the dataset, there is a slight but steady increase in cost, plateauing again near 60 EUR/ton. These outcomes may indicate that cost and effectiveness must be balanced even though the P-graph model offers many workable options.

Based on the graph, it can be inferred that the recycling cost per ton of EoL plastic is not constant across all solutions. The cost increases sharply at the beginning and stabilizes for a significant portion of the solutions before slightly increasing towards the end. This suggests that the P-graph model offers several viable solutions, but a balance must be struck between efficacy and expense. The graph also shows that EoL plastic recycling costs range from 54.9 to 59.28 EUR/ton. With this model, decisions regarding plastic recycling procedures and regulations can be made with generated structures and associated costs.

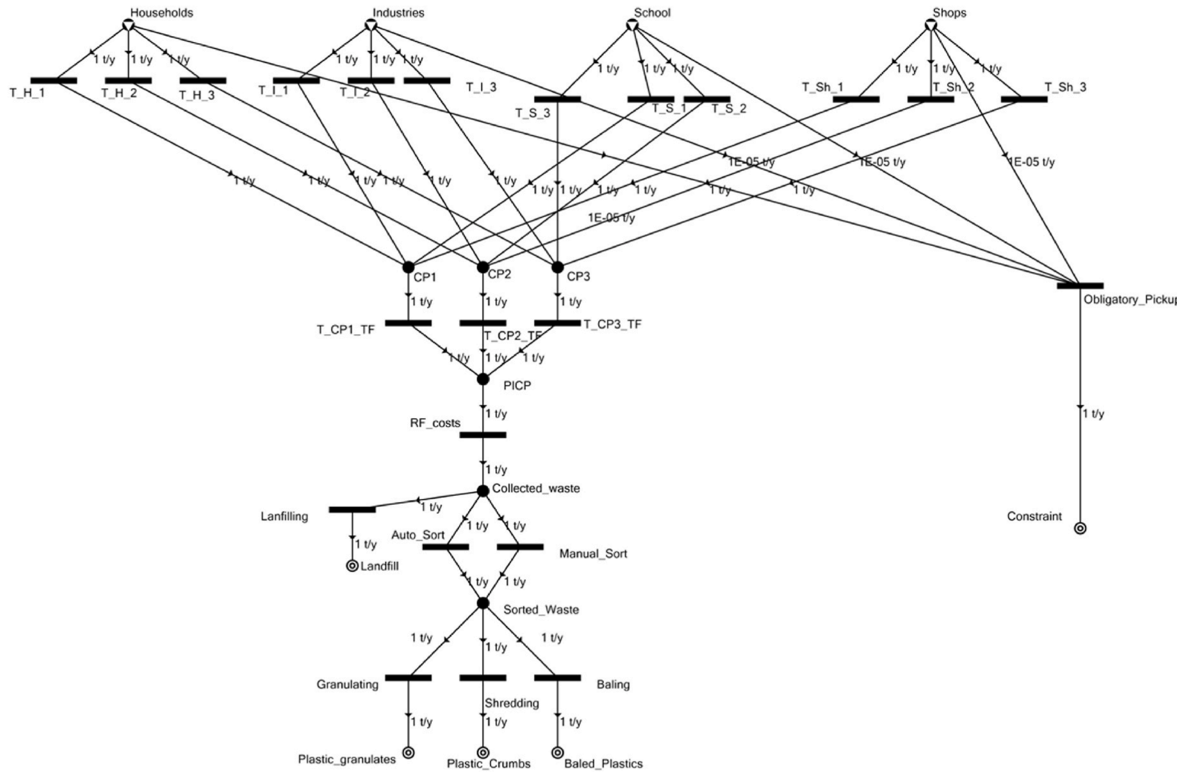

Fig. 6. The maximal structure of the end-of-life supply chain model is considered in the case study.

6. Sensitivity analysis

A sensitivity analysis was carried out to assess the influence of the cost-related parameters in the recycling alternatives for the case study. The CAPEX and OPEX parameters concerning operations for plastics treatment varied from −30 % to +30 %. For the case study, the Cap_{Prop} was not utilized, thus, the analysis was performed for Cap_{Fix}, Op_{prop} and Op_{Fix}. Fig. 9 shows the change in the optimal cost of the plastic recycling scheme concerning the base case presented in Fig. 7(a)–i.e., 647,313 EUR/y. The parameter with the highest influence was the fixed operation cost of the manual sort, which corresponds to the labour expenses of the operation. An interesting result is that the variation of some parameters resulted in a modified structure with different operations for the optimal recycling scheme. This is indicated in Fig. 9 using cell colours.

7. Discussion

There have been recent technological developments plastic recycling pathways. For example, thermal plasma technologies convert EoL plastic into valuable products at high temperatures and energy densities. Thermal plasma treatment ionizes gases using a high-temperature plasma arc, giving electrons and heavy particles equivalent temperatures. Syngas, a fuel or feedstock for chemical synthesis, is produced by the thermal decomposition of organic molecules, particularly plastics. The joule heating effect results in high gas temperatures exceeding 10,000 K, and with (10–100 electron volts (eV), a plasma torch breaks down complex polymers. In high-energy environments, pyrolysis and gasification can convert polymers into liquid fuels, gases, or vitrified materials. Thermal plasma technologies may treat various plastics, making them suitable for distinct EoL streams (Pullao et al., 2024).

In recent years, plasma, Fenton, and electrochemical methods have been developed to upcycle EoL plastics under moderate conditions and effectively eliminate microplastics. Plasma systems' high initial cost may limit their usage. Plasma technology and reactor design advancements are expected to boost efficiency and reduce costs (Kijo-Kleczkowska and Gnatowski, 2022). Thermal plasma therapy is greener than traditional incineration. Plasma methods minimize incomplete combustion-produced dioxins and furans due to their high temperatures. Inerting harmful medical plastic utensils turns into energy using a plasma furnace, supporting a circular economy (Cai and Du, 2021). However, these new technological pathways alone cannot solve the supply chain problem on a large scale. The identified challenges in the context of various regional difficulties of recycling suggest that the poor quality mixed polymer used by recyclers, plastic chemical additive presence, lack of data management of bioplastic consumption, the import of EoL plastic from overseas (i.e., heavy import from the UK, EU27, and the US (TÜIK Istalat Istatistikleri (2017–2021), 2021), ambiguity on legal aspects, source separation, and market availability for recycled plastics, high recycling costs, cheap landfilling costs, and linear rather than circular plastic management practices, are prime reasons for 90 % of MSW ending up in landfills. Turkey contributes the highest share of European marine plastic pollution, has increased its use of virgin materials, and has imported recycled pellets since the 2017 import restriction. Taiwan saw a two-fold rise in EoL paper and plastic imports, and excessive plastic consumption in recreational activities is partially caused by individual behaviour.

However, the supply chain of the recycling sector is challenging due to contaminants in the EoL streams brought on, among other things, by improper disposal, treatment with the appropriate tools, or poor product design (Jäger-Roschko et al., 2020). The literature research recommends ways to lessen EoL plastic's adverse economic, social, and environmental effects. Carbon footprint reduction, adoption of recycling-oriented product design by manufacturers, integration of informal recyclers into formal collection and recycling channels, upgrading and commercializing bio-based plastic, financial incentives to encourage recycling over incineration, landfilling, and preventing releases into the environment are some of these solutions. As mentioned in Table S1, several state governments adopted legislation on EoL plastic separation and new rules on importing recyclable plastics with tight border control

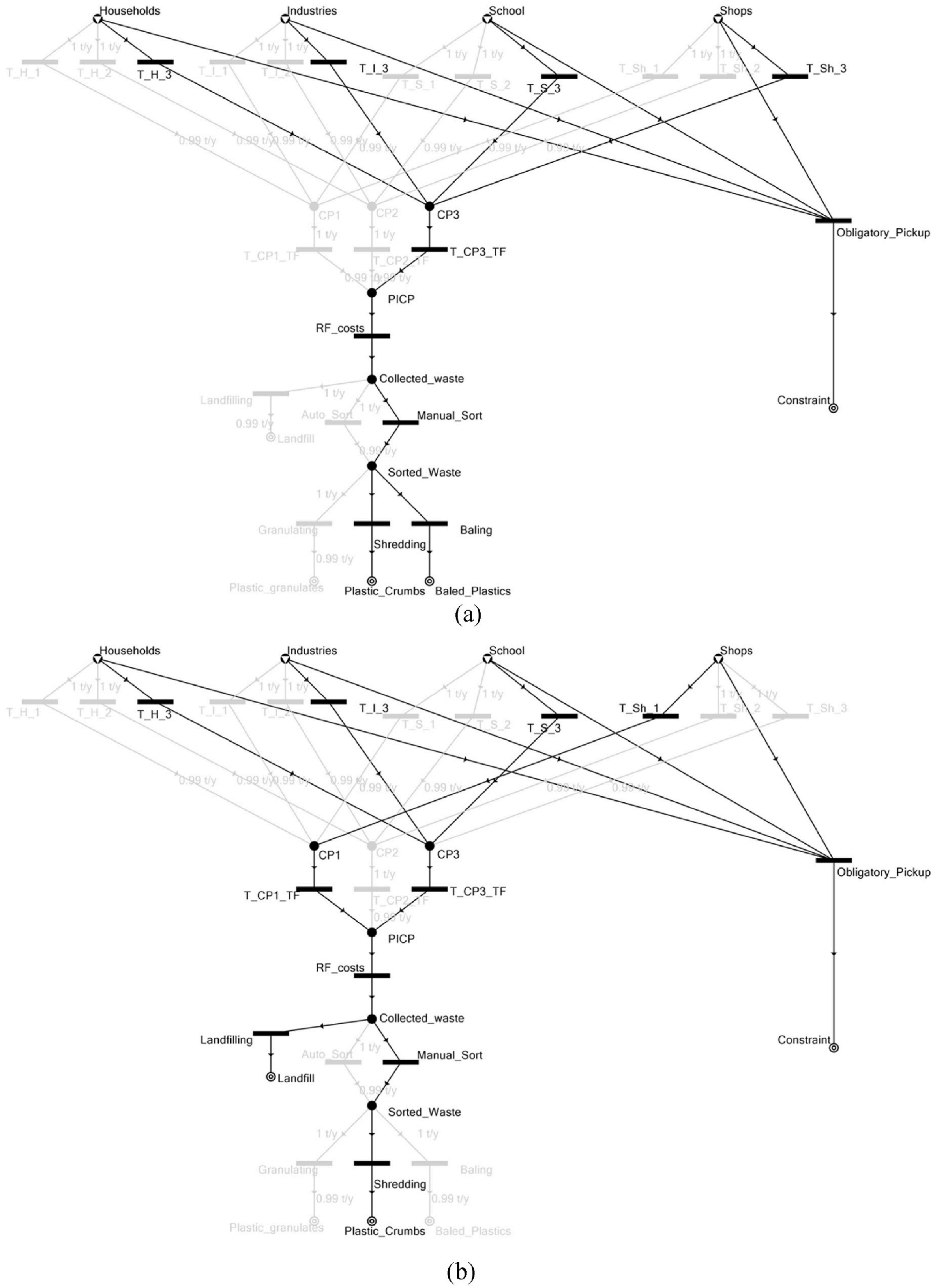

Fig. 7. Visual depiction of end-of-life supply chain solutions found via algorithm ABB with **(a)** lowest costs (647,303 EUR/y) and **(b)** highest costs (698,154 EUR/y)

to increase the quantity of recovered MSW plastics. Solutions for mitigation and optimal supply chain should be based on combining economic and non-economic measures for maximum efficiency.

The divergence in plastic recycling costs between our analysis in Hungary and the study by (Rudolph et al., 2017) in the U.S. can be attributed to inherent economic distinctions. Variances in labour costs, real estate expenses, and overall operational overheads significantly influence these disparities. Hungary's comparatively lower labour costs

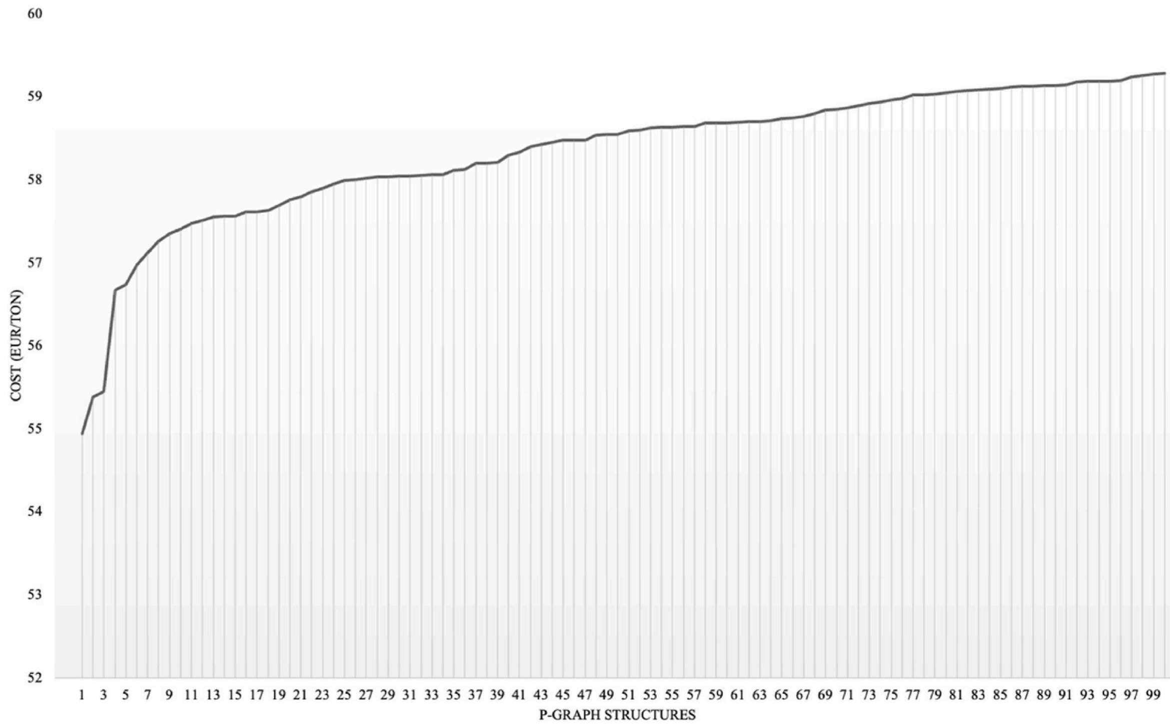

Fig. 8. Total recycling costs for the 100 most cost-effective end-of-life supply chain solutions generated by the P-graph model.

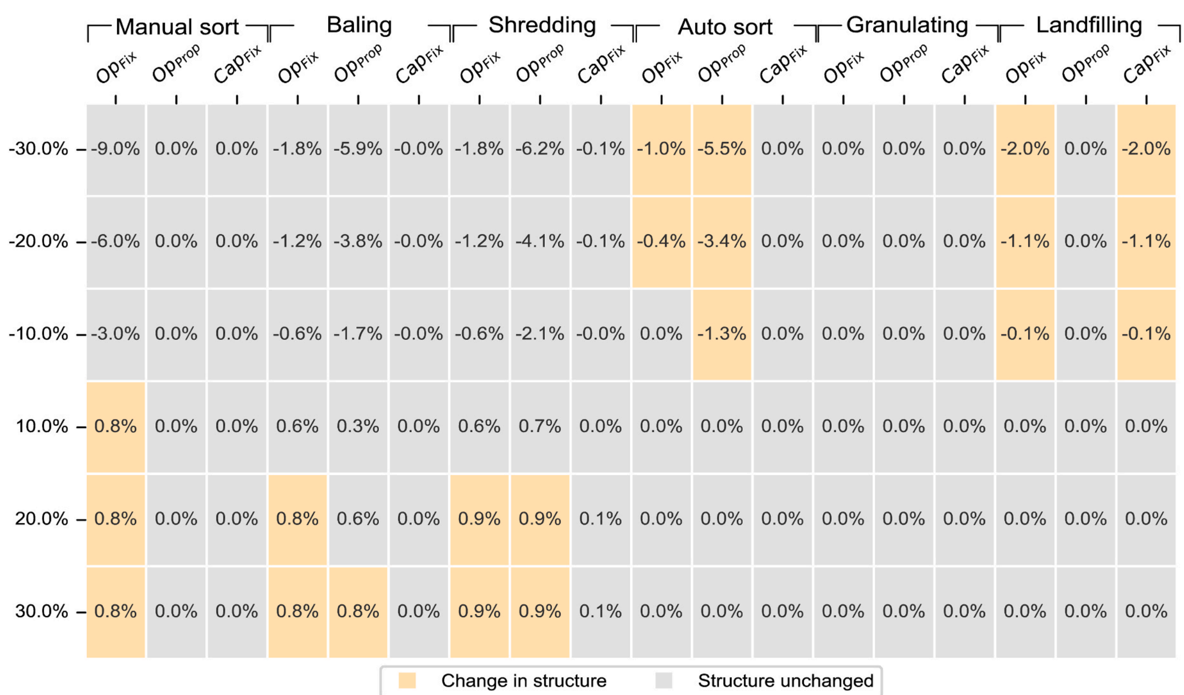

Fig. 9. Change of the optimal treatment cost compared to the base case (Fig. 7(a)) for variations in the units' CAPEX and OPEX parameters for the case study. Variations resulting in a change of the optimal structure's units are shown in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and real estate expenses, shaped by distinct economic contexts, contribute to a more economically viable plastic recycling scenario. Factors such as regulatory frameworks, EoL management infrastructure, and economies of scale also differ between the U.S. and Hungary, influencing overall costs. In Hungary, the range of 54.9–59.28 EUR/ton aligns with regional economic dynamics, providing an economically sound estimate for plastic recycling within the Hungarian context.

As fully disclosed in the manuscript, this work focuses on aiding decision-makers to design cost-efficient plastic recycling pathways since profitable enterprises look for economic benefits when designing and implementing commercial-scale products, process technologies, and logistics. Also, process systems engineering employs economic objectives to minimize costs and maximize profits to optimize a supply chain and achieve profitable and sustainable solutions. Environmental considerations addressed in future studies will encompass a broader range of holistic sustainability metrics in designing EoL plastic supply chains. However, data availability and quality could affect the accuracy of cost calculations and modelling, and a more comprehensive sensitivity analysis would enhance the robustness of the results. Also, with more data availability, our study would explore all potential EoL pathways and temporal variations in recycling practices and costs.

The P-graph model's adaptability is particularly pronounced in its treatment of cost parameters. By allowing users to input their price data for machine equipment operation (proportional cost), the model becomes a dynamic tool capable of reflecting variations in energy pricing across different regions. This user-driven data input mechanism ensures that the generated pathways are responsive to the nuances of diverse economic and infrastructural contexts, effectively mitigating the limitations associated with predefined cost structures. It is also important that the graph methodology does not present the user with a single solution but a set of possible supply chain structures that can be further assessed heuristically.

The P-graph model used in this study is scalable and can be applied to different EoL material management contexts, ranging from small urban areas to large-scale national recycling networks. The framework is designed to accommodate varying levels of complexity, meaning that additional EoL material types, treatment technologies, and collection strategies can be incorporated as needed. By adjusting the model's parameters, such as transport distances, processing capacities, and sorting efficiencies, it can be tailored to regional or national EoL material management infrastructures, making it a versatile tool for optimizing plastic recycling supply chains.

8. Conclusion

This study embarked on a methodological journey to optimize cost-effective pathways for recycling plastics within the EoL supply chain. At its core, the research introduced a new approach, addressing supply chain optimization; the current study proposes a systematic method for generating cost-effective recycling pathways for plastics. The method is formulated based on the principles of the P-graph framework and can generate the n-best alternatives for recycling in terms of total recycling cost. The formulation of the synthesis problem presented can be implemented in assorted scenarios. It can be extended or reduced to be used with more parameters and complex relationships than those presented here for illustration. Therefore, it can be employed during the recycling pathways' analysis and synthesis phases. In addition, the model enhances flexibility in collection points and accounts for variations in CAPEX and OPEX. Therefore, this research aims to provide a comprehensive and adaptable tool for stakeholders engaged in the intricate challenges of plastic EoL management. In doing so, the study contributes to the ongoing evolution of P-graph applications and strives to bridge existing gaps in modelling plastics at the end of their lifecycle.

A comprehensive case study unfolded throughout the investigation, focusing on the city of Miskolc, Hungary, as an illustration of the application of the methodology. Here, we shed light on the economic feasibility of plastic recycling in a unique urban context, emphasizing its potential implications for broader EoL management scenarios. Our proposed P-graph model enhances this economic contextualization by incorporating varying proportional cost flexibility. This model empowers users to input realistic data, accommodating the economic nuances of the region and assessing optimal pathways. It provides a dynamic tool for stakeholders to make informed decisions based on the economic realities of plastic recycling, fostering adaptability and efficiency in EoL management strategies.

Current optimization efforts, including those presented in this study, primarily focus on economic feasibility, overlooking broader sustainability indicators such as carbon footprint, energy consumption, ecosystem quality, and resource depletion. Future research should extend the P-graph methodology by incorporating LCA metrics alongside economic considerations, allowing decision-makers to evaluate recycling pathways based on both cost-efficiency and environmental performance. Furthermore, existing P-graph models do not fully account for environmental trade-offs associated with different recycling methods, such as mechanical versus chemical recycling. While mechanical recycling is often more cost-effective, it may lead to quality degradation of plastics, limiting circularity, whereas chemical recycling requires higher energy inputs but offers material recovery benefits. A multi-objective optimization approach, combining economic and environmental impact functions, could be developed to systematically evaluate trade-offs between profitability and sustainability.

CRediT authorship contribution statement

Baibhaw Kumar: Writing – original draft, Methodology, Investigation, Formal analysis. **Jean P. Pimentel:** Writing – original draft, Software, Methodology, Formal analysis. **Natalia A. Cano-Londoño:** Writing – original draft, Investigation, Data curation. **Gerardo J. Ruiz-Mercado:** Writing – original draft, Methodology, Conceptualization. **Csaba T. Deak:** Writing – review & editing, Resources, Project administration. **Heriberto Cabezas:** Writing – review & editing, Supervision, Conceptualization.

9. Disclaimer

The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency. Mention of trade names, products, or services does not convey, and should not be interpreted as conveying, official U.S. EPA approval, endorsement, or recommendation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145227.

Data availability

Data will be made available on request.

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